

Plane Stress Fracture Resistance of One Steel Sheet and Two Titanium Sheet Alloys

A. M. SULLIVAN AND C. N. FREED

*Strength of Metals Branch
Metallurgy Division*

October 27, 1971



NAVAL RESEARCH LABORATORY
Washington, D.C.

CONTENTS

Abstract.....	1
INTRODUCTION	1
EXPERIMENTAL PROCEDURE	2
Test Method	2
Materials.....	2
SPECIMEN SIZE CONSIDERATIONS	3
FRACTURE TOUGHNESS CHARACTERISTICS	4
Heat Treatments.....	4
Steel — 4130.....	5
Titanium — 120 VCA	5
Titanium — 6Al-4V	8
CRACK GROWTH CHARACTERISTICS.....	8
Load/COD Regions	8
Steel — 4130.....	9
Titanium — 120 VCA	10
Titanium — 6Al-4V	12
RELATIONSHIP BETWEEN CRACK GROWTH AND FRACTURE RESISTANCE	12
FRACTURE TOUGHNESS AS A FUNCTION OF STRENGTH.....	14
CONCLUSIONS	14
REFERENCES.....	15

Plane Stress Fracture Resistance of One Steel Sheet and Two Titanium Sheet Alloys

A. M. SULLIVAN AND C. N. FREED

*Strength of Metals Branch
Metallurgy Division*

Abstract: The fracture resistance of high-strength thin-sheet alloys can be expressed in terms of the relationship between the stress level and the critical crack size at the commencement of unstable fracture. This relationship is designated by the single parameter K_c , which can be measured with a center-cracked tension specimen.

Three high-strength alloys have been investigated to determine the effect of the specimen geometric dimensions on the K_c fracture toughness value. The alloys were 4130 steel and two titanium sheet alloys, Ti-6Al-4V and Ti-120 VCA. The influence of specimen thickness, crack length/width ratio, and yield strength on K_c was studied.

The fracture resistance of 1/16-in.-thick 4130 steel was determined for two strength levels, and an inverse relationship between strength and toughness was observed. The K_c value of each of the titanium alloys was computed for both 1/8- and 1/16-in.-thick specimens. The 120 VCA indicated a slight decrease in fracture resistance with increasing thickness, while the Ti-6Al-4V demonstrated an increase in toughness for the thicker sheet. The initial crack length had no effect on K_c for any of the alloys over the range of crack lengths investigated.

The fracture toughness, normalized to yield strength, was compared to the strength/density ratio for a spectrum of aluminum, titanium, and steel sheet alloys. An inverse relationship between fracture resistance and strength was manifested.

A crack growth phenomenon, in which crack extension occurs at constant load, was demonstrated. This behavior is related to fracture resistance because it is observed only in the tougher alloys within each metal system. Recognition of this fracture characteristic is crucial to a rational interpretation of fracture toughness.

INTRODUCTION

Fracture resistance may be defined as the strength manifested by a metal in the presence of a crack. While a number of tests have been developed to measure the fracture toughness of metal plate, there is no generally accepted test which can designate this property in thin-sheet alloys.

For high-strength sheet metal which fractures under elastic loads, fracture mechanics principles can be applied to approximate the stress distribution at the crack tip. The local stresses in the vicinity of the crack tip depend upon the nominal stress σ , acting on the specimen and upon the half-length a of the crack. Both of these can be described by the single parameter K_c , defined as the plane stress intensity factor, given by

$$K_c = f(\sigma, a).$$

Thus, by measuring the stress acting on the specimen and the length of the crack just prior to instability, the fracture resistance parameter K_c can be calculated.

NRL Problem M01-24; Project RR 007-46-5431. This report completes one phase of the problem. Work on other phases of the problem is continuing. Manuscript submitted July 22, 1971.

For the engineer who must design structures to be fabricated from a high-strength low-toughness sheet alloy, there is considerable usefulness in the designation of fracture resistance by this fracture mechanics parameter. The characterization of a particular alloy and temper by K_{Ic} permits calculation of the relationship which exists between the failure stress and the critical crack length just prior to the commencement of unstable crack propagation. For a given stress applied to the structure during service, the designer can determine the maximum size of cracks which can be tolerated without initiation of unstable fracture.

EXPERIMENTAL PROCEDURE

Test Method

The center-crack tension specimen has been employed to measure K_{Ic} in this investigation. This specimen configuration was chosen because the stress analysis around the center slit is well documented and the testing procedure is suited for laboratory use (1,2).

The plane stress fracture toughness specimen is presented in Fig. 1. In the center of the specimen a cracklike slit has been introduced by electric discharge, and within the slit has been placed a beam displacement gage instrumented with a four strain-gage circuit. Upon loading, the borders of the slit are displaced and cracks will initiate from the slit tips along a plane perpendicular to the applied stress. The displacement gage will monitor the crack-opening displacement (COD) via an electrical readout to an X-Y recorder; a previous calibration between COD and crack length makes it possible to calculate the crack length at any point during the test (3). Stable crack growth occurs from each slit tip until the total crack reaches a critical length for applied stress, whereupon unstable crack propagation ensues and the specimen fractures. The crack length and stress at the onset of instability are determined, and K_{Ic} can be calculated.

Materials

The fracture resistance of one steel sheet and two high-strength titanium sheet alloys was investigated. The influence of sheet thickness, initial crack length/width ratio, and yield strength on K_{Ic} is included in this report.

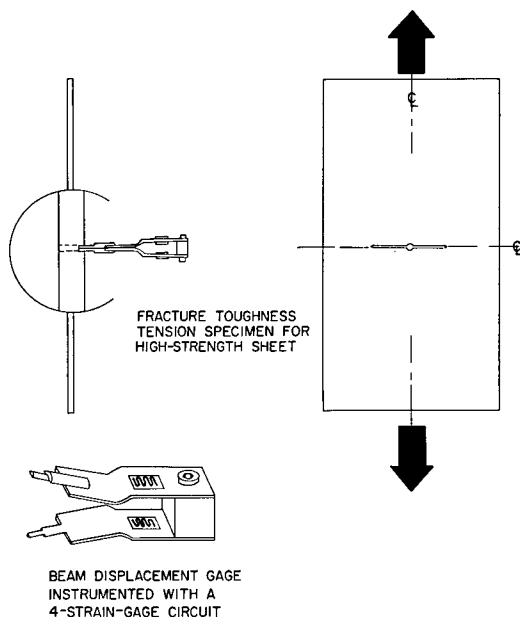


Fig. 1 — Center-cracked tension specimen and beam displacement gage used to monitor crack opening displacement.

Table 1
Heat Treatments of the Sheet Alloys

Alloy	Heat Treatment
4130 ($\sigma_{ys} = 169.5$ ksi)	Austenitize: 1575°F, 1 hr, water spray Temper: 700°F, 30 min, air cool
4130 ($\sigma_{ys} = 178.4$ ksi)	Austenitize: 1575°F, 1/2 hr, water spray Temper: 500°F, 30 min, air cool
Ti-6Al-4V*	Solution Anneal: 1700°F, 20 min, water spray Age: 975°F, 8 hr, air cool
Ti-120 VCA*	Received in solution annealed condition Age: 900°F, 72 hr, air cool

*Both thicknesses (0.063 and 0.125 in.) of each alloy received the same heat treatment.

The steel sheet employed in the program was AISI 4130, a low-alloy metal containing about 1% Cr and 0.1% Mo. Sheet specimens, 0.063-in. (1/16-in.) thick and 12-in. square, were normalized and austenized at the temperatures indicated in Table 1. One group of specimens was tempered at 700°F for 2 hr while a second group was tempered at 500°F for 30 min to achieve two yield strength levels of 169.5 and 178.4 ksi, respectively. The close proximity of the ferrite "nose" to zero time on the isothermal transformation diagram precluded the acquisition of ultrahigh strength properties by heat treatment.

The titanium alloys investigated were Ti-6Al-4V and Ti-120 VCA. The former alloy is a high-alpha lean-beta composition which is responsive to thermal treatment. The metal is widely used in the aerospace industry in such applications as pressure vessels, rocket motor casings, and aircraft structural members. Ti-120 VCA is a metastable titanium alloy capable of heat treatment to very high strengths. The nominal alloy composition of the metal is 13% V, 11% Cr, and 3% Al. Because of the high strength-to-weight ratio which can be achieved, the alloy has found application in high-performance airborne vehicles.

SPECIMEN SIZE CONSIDERATIONS

Earlier work has indicated that specimen dimensions must be sufficiently generous to isolate the crack tip stress distribution from the borders of the specimen (3). Otherwise, the calculated K_c value would not solely be a characterization of the fracture resistance of the sheet but would also depend on the size of the panel which was employed in the test. Specimen dimensions which can influence K_c include the width (W), the crack length/width ($2a/W$) ratio, and the thickness.

An example of the interdependence of specimen width, crack length/width ratio, and the gross stress is presented in Fig. 2. In this three-dimensional drawing, the width, the quantity $2a/W$ and the gross stress are plotted to form a curve surface indicated by the bold lines; every point on this surface is equivalent to a K_c value of $100 \text{ ksi}\sqrt{\text{in.}}$. A requirement for a valid K_c value is that unstable fracture must commence at a stress value less than the yield stress of the alloy. If it is assumed that the yield stress of this hypothetical alloy is 60 ksi, a plane can be drawn through the figure at the 60-ksi level (hatched area) and parallel to the base of the figure. The region lying above the plane represents an area in which yielding has occurred, and the region below the plane indicates an area where valid K_c values can be obtained.

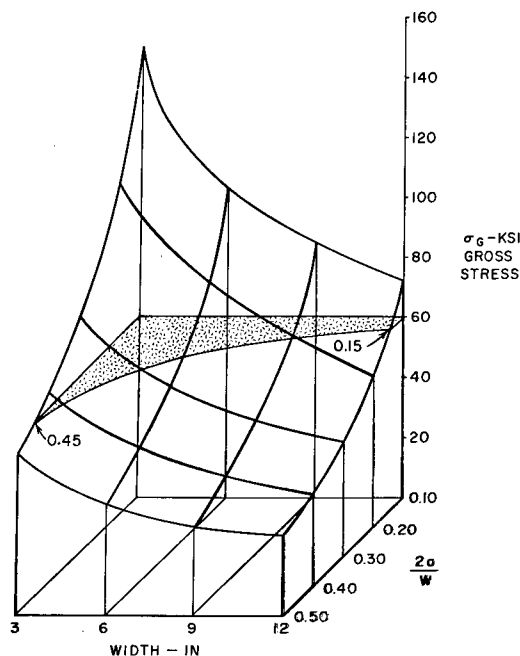


Fig. 2 — Influence of specimen width W , crack length $2a$ (normalized to the width — $2a/W$), and failure stress σ on K_{Ic} . Every point on the three-dimensional surface represents a K_{Ic} value of $100 \text{ ksi}\sqrt{\text{in}}$. For a metal sheet with this K_{Ic} value and $\sigma_{ys} = 60 \text{ ksi}$, all tests in which the gross failure stress lies above the plane represent invalid data, while K_{Ic} tests in which the fracture stress lies below the plane indicate valid K_{Ic} values.

The influence of width and of $2a/W$ on K_{Ic} can now be examined. For this hypothetical alloy, Fig. 2 indicates that if the test panel were 3-in. wide, any $2a/W < 0.45$ would produce invalid K_{Ic} values, i.e., yielding will occur before the K_{Ic} value is attained. As panel width is increased, the region in which valid K_{Ic} values can be obtained grows larger until, at a 12-in. width, any value of $2a/W$ between 0.15 and 0.50 may be employed without invalidating K_{Ic} . A similar analysis can be made holding $2a/W$ constant and determining the minimum width required to achieve a valid K_{Ic} . For example, at small crack lengths where $2a/W$ approaches 0.10, specimen width must be large to prevent yielding.

In addition to the constraints demonstrated in Fig. 2, other restrictions on specimen dimensions exist. For instance, at large crack lengths where $2a/W$ approaches 0.50, the stress distribution at the crack tip may be affected by the edges of the specimen, making K_{Ic} width dependent.

The plot in Fig. 2 was drawn from schematic K_{Ic} and yield strength data, and the restrictions on valid K_{Ic} values are readily ascertainable. In practice, however, the K_{Ic} value of the alloy of interest is unknown. Therefore, the investigation cannot *a priori* determine the specimen dimensions which will assure a valid K_{Ic} test. While some generalizations regarding the toughness can be made from knowledge of the yield strength, the investigator must still perform a series of tests using specimens of varied width and $2a/W$ ratio to obtain assurance that only valid K_{Ic} values will be reported. As more fracture toughness information is gained from different metal systems and strength levels, it will be possible to predict K_{Ic} approximations with greater accuracy, and therefore reduce the number of tests required for each new alloy.

FRACTURE TOUGHNESS CHARACTERISTICS

Heat Treatments

The purpose of applying two different heat treatments to the two thicknesses of 4130 specimens was to obtain distinguishable strength levels among sheets of similar thicknesses. The

mechanical properties recorded in Table 2 indicate that while the yield strengths differed by only 9 ksi between the two series of steel specimens, the differences in tensile strength, reduction in area, and hardness demonstrate a more significant influence of heat treatment.

Each of the titanium alloys received a single heat treatment for both the 0.125 (1/8)-in.- and 0.063 (1/16)-in.-thick specimen series. Their mechanical properties are also presented in Table 2.

The fracture toughness results are tabulated in Table 3 and represented graphically in Figs. 3 to 5. All data represents tests conducted in the "weak" (WR) fracture direction.

Table 2
Mechanical Properties of the Sheet Alloys

Alloy	Fracture Direction	Sheet Thickness (in.)	Yield Strength 0.2% Offset (ksi)	Tensile Strength (ksi)	Elongation (%)	Reduction in Area (%)	Hardness (R _c)
4130	WR	0.063	169.5	192.5	3.9	11.3	40.8
4130	WR	0.063	178.2	225.1	5.3	27.8	46.3
Ti-6Al-4V	WR	0.063	151.1	156.3	1.0	2.0	38.5
Ti-6Al-4V	WR	0.125	146.0	158.2	4.3	7.5	37.0
Ti-120 VCA	WR	0.063	207.3	220.9	2.8	6.3	44.8
Ti-120 VCA	WR	0.125	216.5	227.0	2.3	2.1	45.0

Steel — 4130

The influence of yield strength σ_{ys} on K_{Ic} fracture resistance for the 4130 steel is demonstrated in Fig. 3. The average K_{Ic} value of the lower yield strength sheet was 160.0 ksi- $\sqrt{\text{in.}}$, while the sheet tempered to the higher strength evidenced an average K_{Ic} of 140.8 ksi- $\sqrt{\text{in.}}$. The specimens were 0.063-in. thick and 12-in. wide.

The 4130 steel heat treated to a yield strength of 178.2 ksi contained initial slit lengths $2a_0$ of 2, 3, 4, and 5 in., while the lower strength specimens were slit to lengths of 2, 3, and 4 in. Two lower strength panels were initially drilled in the center of the specimen to create a hole, which was extended with slits to form initial hole/slits of 3 and 4 in. long. The K_{Ic} value was unaffected by the initial slit length-to-width ratio $2a_0/W$ for each strength level throughout the entire $2a_0/W$ range between 0.166 to 0.416.

The fracture resistance for this alloy at both strength levels was moderately high. The K_{Ic}/σ_{ys} ratio of 0.95 for the lower strength specimens and 0.79 for the higher strength panels indicates that fracture occurred well within the elastic region. This moderate toughness is reflected in the length to which a crack must grow before commencement of unstable crack propagation can occur; at a stress level of $\sigma_{ys}/2$, the critical crack length for the higher strength sheet is 1.6 in., while unstable fracture required a crack length of 2.3 in. for the lower strength panels.

Titanium — 120 VCA

The influence of sheet thickness on the fracture resistance K_{Ic} parameter for Ti-120 VCA is shown in Fig. 4. Initial slit lengths of 2 to 4 in. were cut into each of two series of specimens.

Both series received the same heat treatment to achieve similar mechanical properties. The only difference between the two series was specimen thickness; one series was 0.125-in. thick, while the other was 0.063-in. thick.

As Fig. 4 indicates, the fracture resistance of this alloy for either thickness is very low. The K_{Ic} value for the 0.063-in.-thick sheet was 41.5 ksi- $\sqrt{\text{in.}}$, while the thicker sheet manifested a slightly lower value of 35.7 ksi- $\sqrt{\text{in.}}$. The brittle character of Ti-120 VCA at this strength level is better exemplified by noting that if the sheet was stressed to $\sigma_{ys}/2$, the critical crack lengths sufficient to initiate unstable fracture would be 0.10 and 0.07 in., respectively.

Although definitive conclusions are not possible from the limited data, there seems to be no dependence of K_{Ic} on the ratio $2a_0/W$ within the range of crack lengths reported in Fig. 4. If the dependence of large values of $2a_0/W$ on K_{Ic} is based on interference of the crack tip stress

Table 3
Fracture Toughness Data for a 4130 Steel Alloy and Two Titanium Alloys

Alloy	Fracture Direction	Specimen Dimensions			Crack Length $2a$ in K_{Ic} Calculation (in.)	Failure Stress (ksi)	Yield Strength (ksi)	K_{Ic} (ksi- $\sqrt{\text{in.}}$)
		Thickness (in.)	Width W (in.)	Initial Crack Length $2a_0$ (in.)				
4130 ($\sigma_{ys} = 169.5$ ksi)	WR	0.063	12	2.00	2.76	73.3	169.5	156.8
	WR	0.063	12	3.00	3.78	62.9	169.5	163.3
	WR	0.063	12	3.00*	3.72	60.0	169.5	162.2
	WR	0.063	12	4.00	4.80	50.9	169.5	156.3
	WR	0.063	12	4.00†	5.04	48.0	169.5	160.6
4130 ($\sigma_{ys} = 178.4$ ksi)	WR	0.063	12	2.00	2.40	68.0	178.2	135.0
	WR	0.063	12	3.00	3.48	52.0	178.2	128.2
	WR	0.063	12	4.00	4.60	47.3	178.2	140.9
	WR	0.063	12	5.00	5.58	46.0	178.2	159.0
Ti-120 VCA	WR	0.063	12	2.00	2.00	25.3	207.3	45.2
	WR	0.063	12	3.00	3.00	18.0	207.3	40.4
	WR	0.063	12	4.00	4.00	14.4	207.3	38.8
Ti-120 VCA	WR	0.125	12	2.00	2.00	18.0	216.5	32.2
	WR	0.125	12	3.00	3.00	18.5	216.5	41.6
	WR	0.125	12	4.00	4.00	12.3	216.5	33.2
Ti-6Al-4V	WR	0.063	12	2.00	2.16	42.2	151.1	78.8
	WR	0.063	12	3.00	3.12	31.7	151.1	73.0
	WR	0.063	12	4.00	4.38	26.6	151.1	76.4
	WR	0.063	12	5.00	5.38	21.0	151.1	69.4
Ti-6Al-4V	WR	0.125	12	2.00	2.04	53.6	146.0	97.0
	WR	0.125	12	3.00	3.96	32.0	146.0	85.7
	WR	0.125	12	4.00	5.16	26.0	146.0	84.4
	WR	0.125	12	5.00	6.30	24.6	146.0	94.4

*Initial crack consisted of a 2-in.-diam hole with 0.5-in. slits extending radially perpendicular to direction of applied stress.

†Initial crack consisted of a 3-in.-diam hole with 0.5-in. slits extending as above.

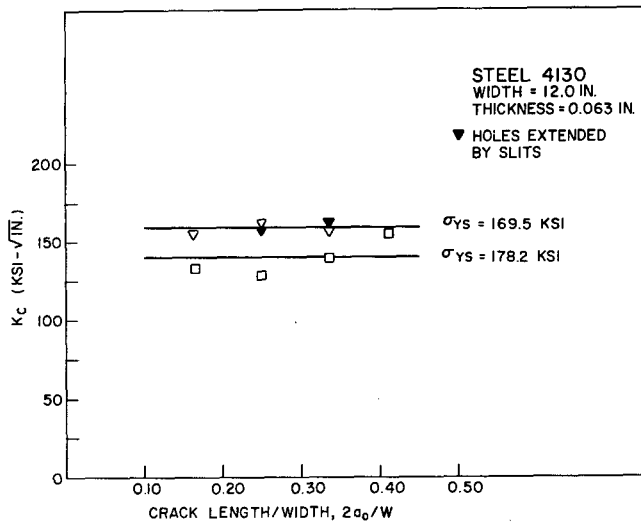


Fig. 3 — For the 4130 steel it is seen that the fracture resistance K_c is inversely proportional to yield strength σ

Fig. 4 — The 0.063-in.-thick Ti-120 VCA manifests a slightly higher K_c value than the 0.125-in.-thick panels. At this strength level, specimens of both thicknesses are brittle.

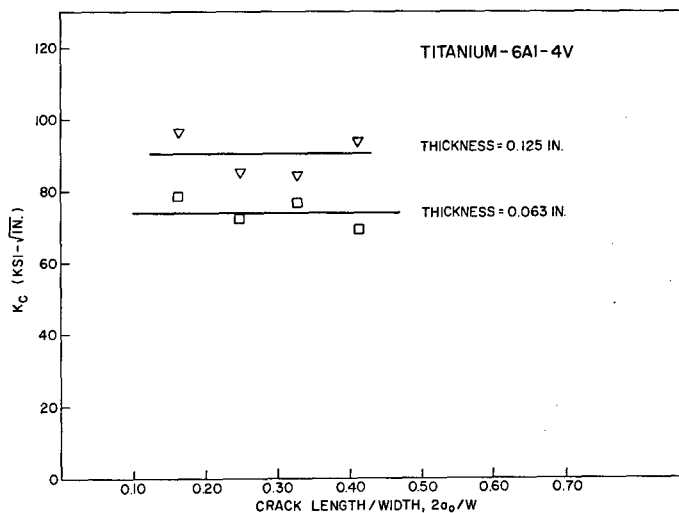
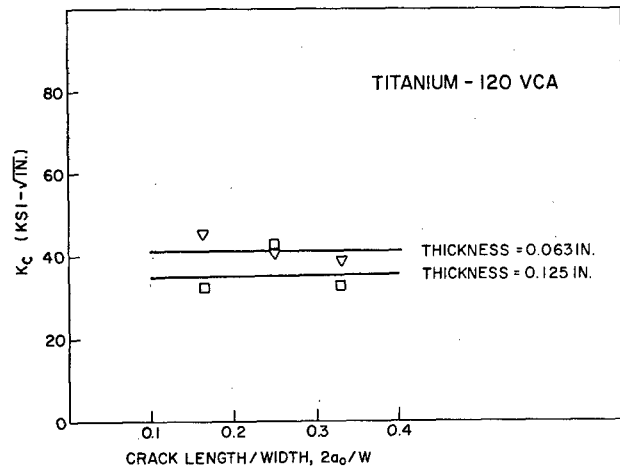


Fig. 5 — The 0.125-in.-thick specimens of Ti-6Al-4V are tougher than the 0.063-in.-thick panels

field with the edge of the sheet, the small values of $2a_o/W$ reported herein, and the localization of the stress field in brittle materials, would mitigate against any influence of $2a_o/W$ on toughness for this alloy.

Titanium – 6Al-4V

The fracture resistance of two thicknesses of this alloy was measured for different values of $2a_o/W$. The results of this study are presented in Fig. 5.

The toughness of the Ti-6Al-4V specimens was about double the K_c values of the higher strength 120 VCA specimens. The thicker (0.125-in.) specimens evidenced a K_c value of 90.4 ksi- $\sqrt{\text{in.}}$, while the toughness of the 0.063-in.-thick specimens averaged 74.4 ksi- $\sqrt{\text{in.}}$. The critical crack lengths at the onset of instability for stress levels of $\sigma_{ys}/2$ are 0.98 and 0.61 in., respectively.

Unlike the data obtained from the 120 VCA specimens, the 0.125-in.-thick Ti-6Al-4V manifested a higher fracture resistance than the 0.063-in.-thick specimens. It is possible that the thickness commensurate with maximum fracture toughness for this strength level will occur at a thickness greater than 0.125 in. A complete survey of the influence of thickness on K_c for this alloy will be conducted. Over the $2a_o/W$ range investigated for both thicknesses, there was no discernible influence of crack length on K_c .

CRACK GROWTH CHARACTERISTICS

Load/COD Regions

An interesting crack growth phenomenon has been observed when the load/COD records of brittle alloys were compared to those which evidenced a moderate degree of toughness. When any metal sheet is loaded in tension, the stress must reach a certain value before a crack will form at the slit tips. In Fig. 6, the COD value normally measured in the K_c test has been replaced by its equivalent in terms of crack length. This load region which precedes crack formation has been designated as Region I in Fig. 6. Once the crack has initiated, it will grow in a stable manner

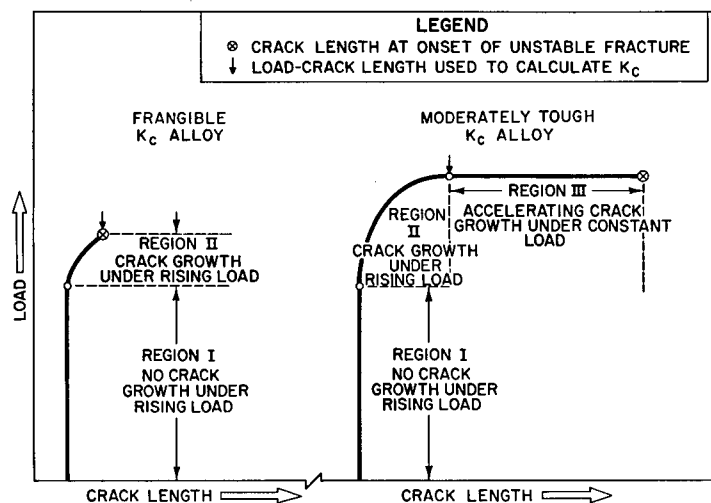


Fig. 6 — Comparison of the load and crack length record of a frangible and of a moderately tough alloy subject to elastic failure.

under a rising load (Region II); if the load is held constant the crack will be arrested within Region II. For the more brittle alloys, once the crack has grown to a critical length, stable crack growth will give way to unstable fracture, leading to instantaneous severance of the specimen.

While the tougher alloys share Region I and II behavior with the more brittle alloys, fracture does not occur under a rising load. Instead, after the crack has slowly grown some distance under a rising load, the crack velocity will markedly increase while the load on the specimen remains constant. The crack will extend at an increasing velocity until instability results in the failure of the specimen. For practical purposes, the point at which the crack begins to grow under a constant load, the beginning of Region III, marks the limit of structural integrity, and the crack length at that point is used to calculate K_c .

The crack growth characteristics were investigated for each of the three alloys and are reported below.

Steel — 4130

The crack growth curve for each of the higher strength 4130 panels is drawn in Fig. 7. In each case the crack growth was stress dependent until a stress level was attained at which the crack extended at a constant stress, culminating in fracture after 1 to 3 in. of crack extension. The closed triangles indicate the stress and crack length from which K_c was calculated for each specimen.

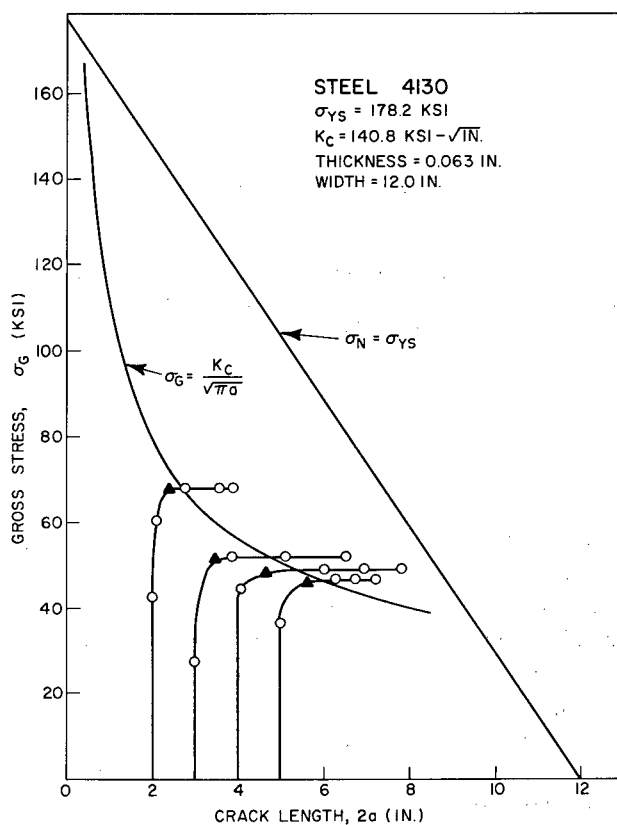


Fig. 7 — Crack growth behavior of the higher strength 4130 steel manifesting crack extension at constant load. Closed triangles indicate stress and crack length values used to calculate K_c . The hyperbolic curve indicates the average K_c value for these specimens. The area to the left of the diagonal line indicates the region in which the net stress σ_N is less than the yield stress σ_{ys} .

The hyperbolic curve intersecting each of the crack growth curves represents the average K_c value ($140.8 \text{ ksi}\sqrt{\text{in.}}$) for this high-strength sheet. The straight line drawn diagonally across the figure designates the locus of points on which the net stress σ_N is equal to the yield stress σ_{ys} ; any point on the crack growth curves lying to the left of the line indicates a stress less than the yield stress. As all of the closed triangle points lie to the left of the diagonal, all of the specimens fractured well below the yield stress.

The crack growth curves for 4130 sheet steel heat treated to the lower yield strength level of 169.5 ksi are presented in Fig. 8. All of the curves display the same characteristic of crack propagation at constant stress as did the higher strength steel panels.

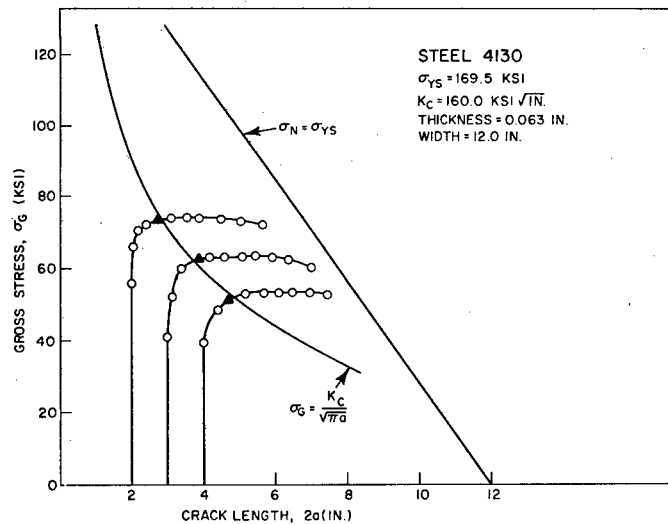


Fig. 8 — Crack extension behavior of a lower strength 4130 steel. (Compare with Fig. 7.) The area to the left of the diagonal line indicates the region in which $\sigma_N < \sigma_{ys}$.

Titanium — 120 VCA

With only one exception, the 120 VCA specimens manifested no stable crack growth prior to unstable fracture. As indicated in Figs. 9 and 10, most of the specimens fractured instantaneously upon reaching maximum load. This fracture behavior was independent of initial slit length, within the range of 2 to 4 in., and occurred in both 0.125- and 0.063-in.-thick specimens.

When an electric discharge is used to cut a slit in a specimen, the slit tip radius may vary between 2 and 5 mils. If slow stable crack growth precedes unstable fracture, the crack tip radius should be sufficiently similar from specimen to specimen to provide reproducible K_c values for that alloy (4). When no crack growth precedes instability, it may be argued that the relatively blunt slits provide less of a stress concentration than a sharp crack, and this would influence the crack tip stress distribution. The effect would be to overestimate K_c for the blunter slit tip.

For practical purposes, any overestimation of K_c for this brittle alloy would have little engineering significance. However, specimens will be tested in which the slit tips are sharpened by fatigue cracks to determine if K_c is influenced by slit tip radius for highly brittle alloys.

Fig. 9 — Frangible alloys are more likely to fracture instantaneously upon reaching the maximum load (open circle) than to extend under constant load.

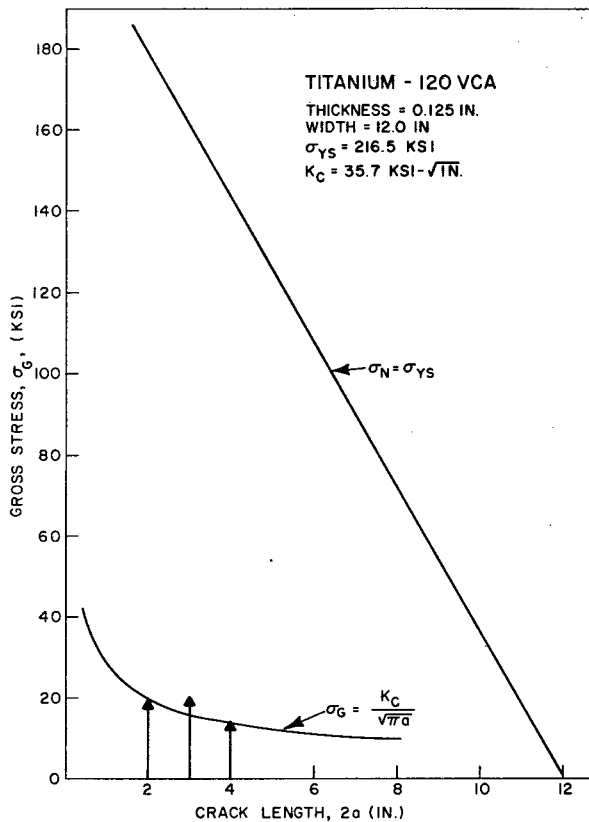
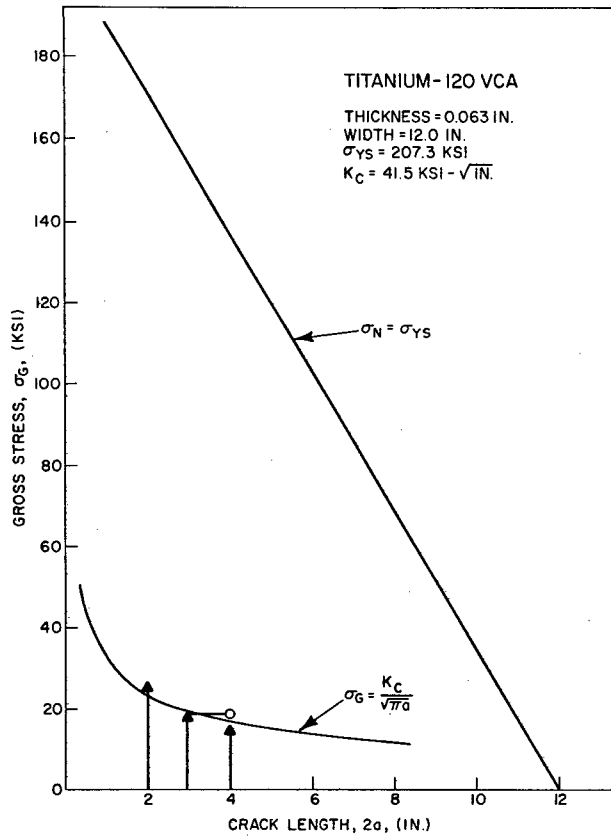


Fig. 10 — The phenomenon in which a crack grows at constant load does not occur for the ultrahigh-strength Ti-120 VCA

Titanium — 6Al-4V

The crack growth characteristics for the Ti-6Al-4V alloy are plotted in Figs. 11 and 12. All of the 0.063-in.-thick specimens displayed sufficient crack extension prior to fracture to obviate the possibility that the recorded K_c values were affected by the crack tip radius. One specimen in the 0.125-in.-thick series evidenced less than 10 mils of crack growth prior to fracture; the K_c value for this specimen was slightly higher than the average K_c for the series. The influence of a fatigue crack at the slit tip on K_c is currently being investigated.

It should be noted that the constant- K_c hyperbolic curve drawn in each of these figures was based on the infinite sheet formula, whereas the closed triangles which indicate the K_c value for each specimen were calculated with the Isida finite width equation (5). This accounts for the deviation between the mean value of the closed triangles and the position of the constant- K_c curve.

RELATIONSHIP BETWEEN CRACK GROWTH AND FRACTURE RESISTANCE

The relationship between the phenomenon of crack growth at constant stress and toughness is presented in Table 4. The fracture resistance parameter K_c is normalized to σ_{ys} in order to eliminate strength as a variable. The resultant K_c/σ_{ys} ratio is related to the crack growth characteristics manifested by each specimen. Aluminum alloys that have been previously reported (6) are included in this table to provide maximum data from which conclusions may be drawn.

The level of toughness which distinguishes between Region III behavior as defined in Fig. 3 and fracture in the absence of constant-stress crack extension differs with each metal system. For aluminum alloys, all specimens which evidenced a $K_c/\sigma_{ys} > 1.22$ exhibited constant-

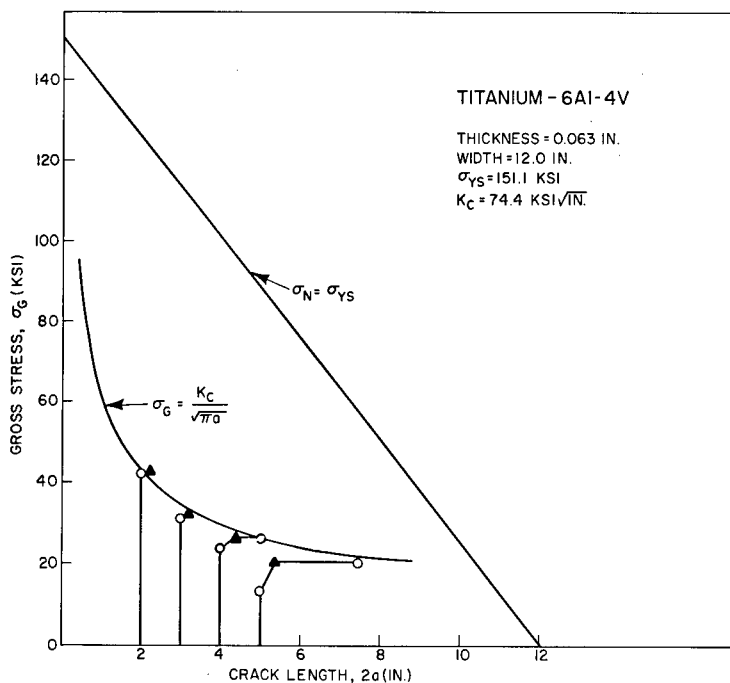


Fig. 11 — Constant-load crack growth occurred in Ti-6Al-4V specimens containing the longer initial slit lengths.

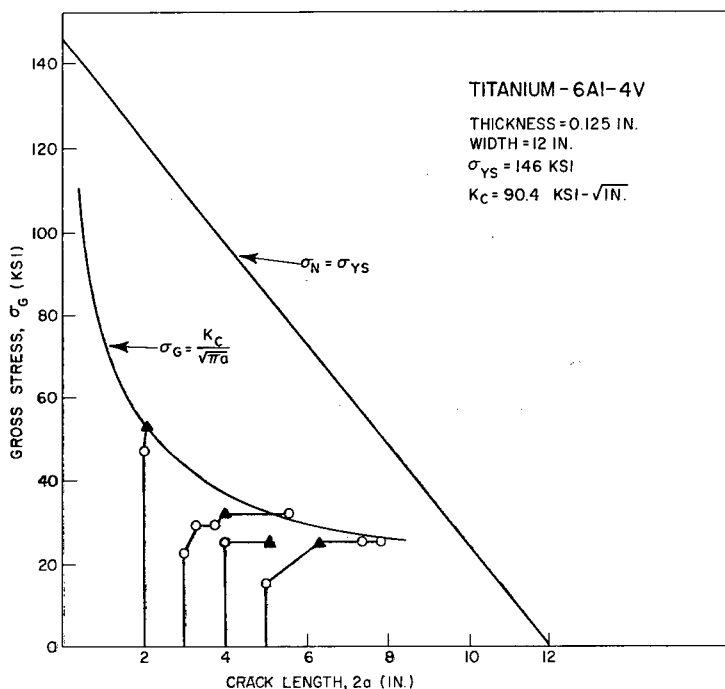


Fig. 12 — Crack growth curves for 0.125-in.-thick Ti-6Al-4V

stress crack growth, while all specimens with a ratio of 0.85 or less did not evince this behavior. The more limited titanium data indicate that when the K_{IC}/σ_{YS} ratio is between 0.49 and 0.62, a transition is occurring between those fracture panels which exhibit constant-stress crack propagation and those which do not. The steel alloy data indicate that Region III behavior extends to ratios below 0.79.

The phenomenon of crack extension at constant stress, referred to as Region III behavior, has more significance than mere experimental observation. Whether K_{IC} is calculated using the crack length at the inception or at the conclusion of Region III can mean a considerable difference in reported K_{IC} values. For instance, the K_{IC} value is 160 ksi- $\sqrt{\text{in.}}$ for one typical 4130 steel specimen (shown in Fig. 8) if the crack length at commencement of constant-stress crack growth is used; if the crack length just preceding instantaneous failure is used, the reported K_{IC} value would have been 240 ksi- $\sqrt{\text{in.}}$ Furthermore, it should be recognized that some experimental procedures which measure K_{IC} are unable to discern the Region III phenomenon. The crack-line-loaded specimen which is well suited to R-curve measurements cannot be used directly to determine if the crack growth behavior is present. In this specimen, the crack moves into a stress field of rapidly diminishing magnitude, which prohibits instability.

The most important reason for selecting the crack length at Region III inception pertains to the use of K_{IC} in design. Assume a scenario in which a structure fabricated from a metal evidencing Region III behavior contains a weld crack that has been extended by fatigue. Once the crack length is sufficient to initiate crack growth under constant stress, the failure of the structure is assured in a short finite time. The critical crack length on which the designer should rely is indicated by Region III commencement. Calculation of a " K_{IC} " from a longer crack size representing an arbitrary cutoff between slow unstable propagation and the crack size just prior to instantaneous failure would be dangerously misleading.

Table 4
Crack Growth Characteristics

Alloy	K_{Ic} (ksi- $\sqrt{\text{in.}}$)	Yield Strength (ksi)	K_{Ic}/σ_{ys} ($\sqrt{\text{in.}}$)	Number of Specimens which Manifested Region III Behavior
<u>Steel</u>				
4130 (700°F temper)	160.0	169.5	0.95	4 of 4 tested
4130 (500°F temper)	140.8	178.2	0.79	3 of 3 tested
<u>Titanium</u>				
Ti-6Al-4V (0.125 in.)	90.4	146.0	0.62	3 of 4 tested
Ti-6Al-4V (0.063 in.)	74.4	151.1	0.49	1 of 4 tested
Ti-120 VCA (0.063 in.)	41.5	207.3	0.20	1 of 3 tested
Ti-120 VCA (0.125 in.)	35.7	216.5	0.16	0 of 3 tested
<u>Aluminum</u>				
2024-T3 (0.063 in.) WR	87.0	50.0	1.74	5 of 5 tested
7475-T761 (0.094 (3/32) in.) RW	98.4	60.8	1.62	2 of 2 tested
7475-T61 (0.094 in.) WR	88.4	73.3	1.21	2 of 2 tested
RW	93.6	74.7	1.25	2 of 2 tested
7075-T6 (0.063 in.) WR or RW	65.2	76.5	0.85	0 of 15 tested
7178-T6 (0.063 in.) WR or RW	55.4	78.9	0.70	0 of 32 tested

FRACTURE TOUGHNESS AS A FUNCTION OF STRENGTH

The relationship between fracture resistance and strength for seven alloy sheets is presented in Fig. 13. Yield strength is normalized to density on the abscissa, and K_{Ic} is normalized to yield strength on the ordinate to permit comparison of steel, titanium, and aluminum alloys. The strength/density ratio is also a criterion used by aerospace designers to compare the structural efficiency of different metals.

The inverse correspondence between toughness and yield strength for sheet alloys is demonstrated in Fig. 13. Those alloys which would permit maximum weight savings in a structure are most susceptible to failure by unstable fracture emanating from very small flaws. Titanium alloys evidence higher strength/density ratios than aluminum sheet alloys but indicate a concomitant loss in toughness. Further investigation will be required to determine whether the K_{Ic}/σ_{ys} ratio for the titanium and steel alloys can be increased with improved heat treatment.

CONCLUSIONS

1. The K_{Ic} fracture resistance of two series of 4130 steel alloy specimens, each series heat treated to a different strength level, indicates an inverse relationship between strength and toughness.

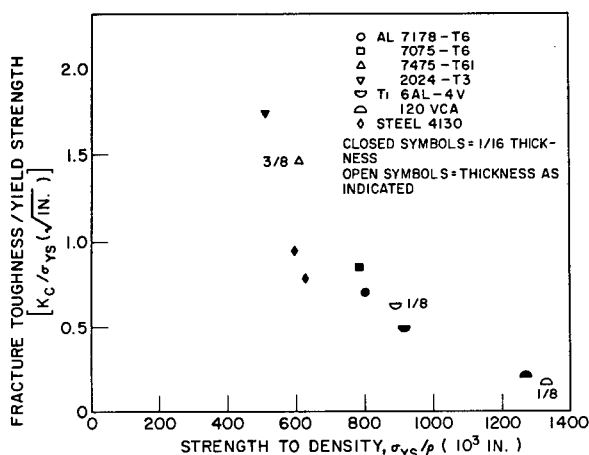


Fig. 13 — Relationship between the K_c/σ_{ys} fracture resistance ratio and the strength-to-density ratio for seven alloys.

2. Fracture resistance is a function of sheet thickness for specimens of Ti-120 VCA and Ti-6Al-4V: for the Ti-120 VCA, $K_c = 35.7 \text{ ksi}\sqrt{\text{in.}}$ for the 0.125-in.-thick sheet and $41.5 \text{ ksi}\sqrt{\text{in.}}$ for the 0.063-in.-thick specimens; the Ti-6Al-4V, however, indicated a higher K_c for the 0.125-in.-thick sheet than for the thinner 0.063-in. sheet.

3. For the three alloys, the ratio $2a_o/W$ did not influence K_c over the range of crack lengths investigated.

4. A phenomenon in which crack growth occurs at constant stress was observed. This behavior is restricted to the tougher alloys within each metal system. A preliminary distinction is made between those alloys that fracture upon instantaneously attaining maximum load and those which demonstrate constant stress crack extension in terms of K_c/σ_{ys} ratio for each metal system.

REFERENCES

1. Paris, P.C., and Sih, G.C., "Stress Analysis of Cracks," pp. 30-81, discussion, pp. 82-83, in "Fracture Toughness Testing and Its Applications," ASTM-STP 381, 1965.
2. "Fracture Testing of High-Strength Sheet Materials: A Report of a Special ASTM Committee." 1st Chapter of the Report, ASTM Bull. No. 243, pp.29-40, Jan. 1960.
3. Sullivan, A.M., and Freed, C.N., "The Influence of Geometric Variables on K_c Values for Two Thin Sheet Aluminum Alloys," NRL Report 7270, June 1971.
4. Broek, D., "The Residual Strength of Aluminum Alloy Sheet Specimens Containing Fatigue Cracks or Saw Cuts," National Aerospace Laboratory (Amsterdam), Tech. Rept. NLR-TR-M. 2143, 1966.
5. Brown, W.F., Jr., and Srawley, J.E., "Plane Strain Crack Toughness Testing of High Strength Metallic Materials," ASTM-STP 410, 1966.
6. Freed, C.N., Sullivan, A.M., and Stoop, J., "Comparison of Plane Stress Fracture Toughness for Three Aluminum Sheet Alloys," NRL Report 7299 (in press).

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Research Laboratory Washington, D.C. 20390		2a. REPORT SECURITY CLASSIFICATION Unclassified	
		2b. GROUP	
3. REPORT TITLE PLANE STRESS FRACTURE RESISTANCE OF ONE STEEL SHEET AND TWO TITANIUM SHEET ALLOYS			
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) A final report one one phase of the problem; work is continuing on other phases.			
5. AUTHOR(S) (First name, middle initial, last name) A. M. Sullivan and C. N. Freed			
6. REPORT DATE October 27, 1971		7a. TOTAL NO. OF PAGES 19	7b. NO. OF REFS 6
8a. CONTRACT OR GRANT NO. NRL Problem M01-24		9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 7332	
b. PROJECT NO. RR 007-01-46-5431			
c.		9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
d.			
10. DISTRIBUTION STATEMENT Approved for public release; distribution unlimited.			
11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY Dept. of the Navy (Office of Naval Research) Washington, D.C. 20360	
13. ABSTRACT <p>The fracture resistance of high-strength thin-sheet alloys can be expressed in terms of the relationship between the stress level and the critical crack size at the commencement of unstable fracture. This relationship is designated by the single parameter K_c, which can be measured with a center-cracked tension specimen.</p> <p>Three high-strength alloys have been investigated to determine the effect of the specimen geometric dimensions on the K_c fracture toughness value. The alloys were 4130 steel and two titanium sheet alloys, Ti-6Al-4V and Ti-120 VCA. The influence of specimen thickness, crack length/width ratio, and yield strength on K_c was studied.</p> <p>The fracture resistance of 1/16-in.-thick 4130 steel was determined for two strength levels, and an inverse relationship between strength and toughness was observed. The K_c value of each of the titanium alloys was computed for both 1/8- and 1/16-in.-thick specimens. The 120 VCA indicated a slight decrease in fracture resistance with increasing thickness, while the Ti-6Al-4V demonstrated an increase in toughness for the thicker sheet. The initial crack length had no effect on K_c for any of the alloys over the range of crack lengths investigated.</p> <p>The fracture toughness, normalized to yield strength, was compared to the strength/density ratio for a spectrum of aluminum, titanium, and steel sheet alloys. An inverse relationship between fracture resistance and strength was manifested.</p> <p>A crack growth phenomenon, in which crack extension occurs at constant load, was demonstrated. This behavior is related to fracture resistance because it is observed only in the tougher alloys within each metal system. Recognition of this fracture characteristic is crucial to a rational interpretation of fracture toughness.</p>			

UNCLASSIFIED

14

KEY WORDS

LINK A

LINK B

LINK C

ROLE

WT

ROLE

WT

ROLE

WT

Fracture properties

Fracture tests

Tensile strength

Toughness

Titanium alloys

Alloy steels